Essay

Using microorganisms for a sustainable agriculture in Mexico: considerations and challenges

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Abstract

Numerous plant species of agricultural interest establish symbiosis with soil microorganisms, such as microorganisms that promote plant growth, which provide great benefits because they help to reduce the excessive use of fertilizers and pesticides used in agricultural production. Currently, Mexican agriculture is looking for environmentally friendly fertilization alternatives. That is why sustainable agriculture practices can only be successful when producers have all the means to implement them properly. This essay addresses issues on the considerations and challenges for the development of a sustainable agriculture in Mexico through the use of beneficial microorganisms, and it presents the current and future outlook on their use taking into account the benefit to the producer.

Keywords: biofertilizers, microorganisms in the soil, sustainability.

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Levels of food insecurity globally are very high due to the high rate of population growth and limited innovation for the sustainability of agricultural production systems. The importance of food security is given from a socio-economic point of view, but also from the point of view of access to natural resources and agriculture, and its impact on the resources of a country (Urquía-Fernández, 2014). Around the world there is a wide demand for food in developing countries that, despite having the natural and genetic resources for the production of their food, their production does not meet the demand and it is not sustainable (Sosa, 2017).

One way to mitigate these effects is to know their origin, which are the ways in which food is produced in these communities, shaping the concept of sustainable agriculture. This focuses on long-term production, both livestock and food, impacting as little as possible on the environment from its biotic and abiotic factors (Waseem *et al*., 2020). The accumulation of knowledge in communities or regions with little access to technology or sustainable practices allow producers to gradually be self-sufficient and have greater productivity without too much damage to their own resources, in many cases, the main one is the rational use of water and agricultural practices compatible with land use management, the success for the implementation of these practices is the adoption of such technologies (Fielding *et al*., 2008).

Of course, the implementation of sustainable agriculture practices can only be successful when producers have all the means to implement them properly, an example is what was done with sustainable banana production, among various conclusions presented, socioeconomic and psychosocial factors were identified as those that limit the implementation of sustainable practices in agriculture (Waseem *et al*., 2020).

According to the National Academy of Sciences of the United States of America, agricultural production (organic or conventional) is considered sustainable if and only if adequate quantities of high-quality food are produced, without intervening in the natural resource base and the environment, being economically viable, contributing to the well-being of farmers and their communitys (Reganold and Wachter, 2016).

Results and challenges of sustainable agriculture

Conventional agricultural production methods are not producing enough food to meet the food needs of the growing national population (FAO, 2014). Conventional agriculture practices are having effects related to climate change, this due to the use of fossil fuels, agricultural machinery, fertilizers and chemical fertilizers, which generate greenhouse gases, aggravating the problem since not only is food security at risk, but also environmental damage is increased (López and Rodríguez, 2014).

Mexico is one of the countries most committed to mitigating climate change through concrete actions, having signed the Kyoto Protocol (1997) and designed the national climate change strategy (ENCC) in 2007, which defines actions involving sustainable agriculture, such as reducing emissions from the use of fertilizers and conservation tillage to maintain carbon stocks and increase capture capacities (SAGARPA, 2014).

National strategies have defined concrete actions to follow, but other types of tools have also emerged, such as the National Network for Sustainable Rural Development (Rendrus), created in Mexico in 1996, with the aim of strengthening rural producers by identifying, systematizing and exchanging successful business experiences, the establishment of this network allowed an efficient proposal for the use of methodologies to evaluate sustainability and training regarding sustainable agriculture was provided to producers (Pastor-Pérez *et al*., 2016).

In addition to the strategies used to technically implement sustainable agriculture, in recent years there has been an increase in the use of microorganisms associated with crops, to contribute to the reduction of the use of synthetic fertilizers and mitigate the environmental pollution caused by them (Chávez-Díaz *et al*., 2020). There have been important results and advances in terms of sustainable agriculture, there are still challenges for the implementation of these agricultural models (Bergel, 2020).

One of the main challenges is associated with the economy of producers, due to the perception and balance they make regarding the economic cost/benefit in the short, medium and long term, since there is still some skepticism on the part of end users, although production with sustainable techniques represents little or almost no investment in the short or medium term it represents a cost to them because they cannot respond to market demand in terms of productivity; however, in cases where they consider the long-term view, the balance is again tilted towards sustainable agriculture by considering the cost of soil deterioration, loss of land fertility and multifunctional agricultural services (Gerritsen *et al*., 2012).

Despite the progress made as a result of national work in the field of research, dissemination and application of the knowledge generated, progress on the regulation and legislation of the use of microorganisms for biofertilization is still limited. In general, the main challenge that must be addressed so that agriculture can be called sustainable is to ensure the necessary amount of food for the future, at the same time that the use of the land is efficient, the impact on the environment is reduced and the economy of farmers is improved (López and Rodríguez, 2014).

Importance of microorganisms in the soil

The microbial activity of the soil, and its benefits on it, is strongly impacted by unsustainable intensive agricultural practices and climatic conditions, through modifications of soil characteristics at the physical, chemical and biological level; for example, temperature, humidity, salinity, aeration, oxide-reduction state, content and composition of gases in the porous space, bioavailability of nutrients, pH (Ibarra-Villarreal *et al*., 2021). In this way, the imbalance in soil microbial communities triggers processes of biological degradation, reducing crop yield/quality by increasing vulnerability to various types of stress and limiting the ability to carry out their main ecosystem services, such as: plant biomass production, nutrient storage and recycling, water storage and filtering, climate and flood regulation, climate change mitigation and habitat for biological activity (Díaz-Rodríguez *et al*., 2021).

The bioprospecting of microorganisms that live in the soil represents a promising tool for the development of sustainable agricultural practices focused on meeting the demand for food associated with the global population increase [which is projected to reach 10 billion inhabitants by 2050 and consequently it will require an increase in food production between 70 and 100% (FAO, 2017; De los Santos-Villalobos *et al*., 2018)].

Microbial communities in soils conduct between 80 and 90% of the biological processes developed in the soil (Bajsa *et al*., 2013), due to its multiple ecological niches, among which the next stand out, the mitigation of exogenous alterations, promotion of plant growth, biocontrol activity, nutrient cycling, production of plant biomass, soil structure and fertility, the degradation of toxic compounds, among others (Delgado-Baquerizo *et al*., 2016).

Among this microbiota, there is a particular set called plant growth promoting microorganisms (MPCV), which directly or indirectly favor vegetative growth, generate tolerance to abiotic and biotic stress in the plant, facilitate the nutrition of the plant and antagonize phytopathogens in host plants. Among the most studied microbial genera of this group the next stand out, *Pseudomonas*, *Enterobacter*, *Bacillus*, *Variovorax*, *Klebsiella*, *Burkholderia*, *Azospirillum*, *Serratia*, *Azotobacter* and *Trichoderma* (*teleomorph Hypocrea*) (Dohrmann *et al*., 2013).

The production of peptide antibiotics and metabolites that protect plants from possible attacks by pathogenic organisms are among the metabolic capabilities of MPCV strains; they also stimulate the immune system of the plant to protect them against infections by bacteria, fungi, or pathogenic nematodes (Valenzuela-Ruiz *et al*., 2020). On the other hand, various strains of MPCV have the ability to synthesize phytohormones, both to regulate plant growth and development and to increase the bioavailability of nutrients in the soil, thus allowing better nutrition of the plant (Orozco-Mosqueda and Santoyo, 2020).

As well, MPCVs have the ability to fix atmospheric nitrogen and solubilize phosphorus (mechanisms that provide nutrients to plants, mitigating environmental pollution events caused by the application of synthetic fertilizers), as well as iron sequestration by siderophores that prevents the development of phytopathogens, when their growth depends on this element (Valenzuela-Aragón *et al*., 2019; Rojas-Padilla *et al*., 2020).

In this way, beneficial soil microorganisms with application in agriculture can be divided into 1) phytostimulants, which enhance seed germination, rootedness, and plant growth through the production of growth regulators, vitamins and other substances; 2) improvers, which favor the structure of the soil and its physicochemical properties due to the formation of aggregates, which increases its fertility; 3) bioremedials, these are associated with the elimination of recalcitrant synthetic and highly harmful agricultural inputs to the environment and human health, such as pesticides, herbicides, among others; and 4) biofertilizers, which have the ability to provide bioavailable nutrients and bioactive molecules for the growth and increased development of plants, including the control of phytopathogens (Joshi *et al*., 2019).

Biofertilizers, prior to their use, must be analyzed based on the problem to be addressed, their capacity for colonization of the soil and the plant, the synthesis of bioactive compounds of interest and the native microbial communities (Chávez-Díaz *et al*., 2020), since its activity of promoting plant growth can be focused on different levels of action, i.e. metabolic activities for the solubilization or mineralization of nutrients, the biosynthesis of widely studied or undiscovered beneficial metabolites, the production of antagonistic compounds of phytopathogens (Díaz-Rodríguez *et al*., 2021).

The importance of soil microorganisms and their close relationship with sustainable agriculture depends on the use of the metabolic and functional diversity of MPCVs (Figure 1). For this, it is crucial to focus efforts and financing for the bioprospecting of beneficial microbial communities and determine their role in the complex network of physical, chemical and biological interactions occurring in the soil, which will lead to the design of sustainable strategies to improve soil fertility and health, the production and quality of agricultural crops and mitigate the negative economic, environmental and health impact of the use of unsustainable intensive agricultural practices.

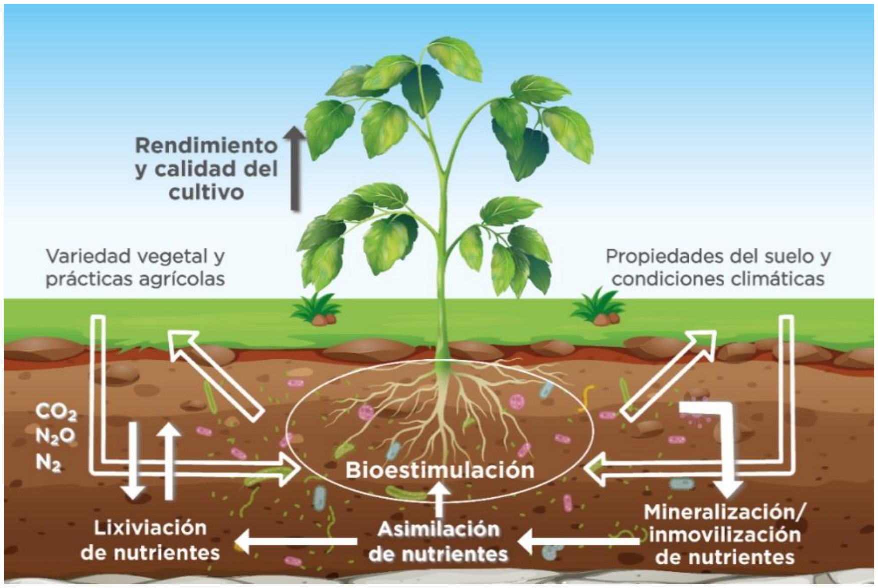

Figure 1. Biological processes regulated by microorganisms involved in soil fertility and plant productivity.

Microorganisms in sustainable agriculture

Sustainable agriculture seeks to maintain in balance the microbial communities (bacteria, fungi, protozoa, and viruses) associated with agricultural crops, this is the phytomicrobiome, since the diversity, stability and resilience of the phytomicrobiome are the main determinants of the productivity and plant health of an agroecosystem (Basu and Kumar, 2020). MPCVs, through different types of symbiotic relationships they establish with plants, carry out direct and indirect beneficial mechanisms to promote plant growth.

Based on the mode of action presented by MPCVs, these can be used for the development of bioproducts, such as biofertilizers, phytostimulants, biofungicides or biopesticides (Mamani and Filippone, 2018). Generally, these microbial inoculants contain one or more strains that have different mechanisms of action, so they can be used at different stages of the culture crop; however, it is necessary to develop the appropriate formulation, production and management systems to ensure the survival and effective establishment of MPCVs in the plant, as well as to monitor the effect they have on the previous microbial community and the stability of the new generated community (Richardson and Simpson, 2011).

In this sense, biotechnological and molecular techniques can help to better understand the mode of action of MPCVs to establish successful plant-microorganism interactions and a favorable application of MPCVs (Khalid *et al*., 2009), to consider the phytomicrobiome as an integral part of plant breeding programs in the near future (Córdova-Albores *et al*., 2021).

Development of an ecological approach to the choice of microbial inoculants in Mexico

As for the origin of the organisms used as biofertilizers, there are data that show the importance of the identity of the symbionts to increase the efficiency of the association and the benefits for the plant; for instance, light (Villegas *et al*., 2017) and low temperatures cause changes in the colonization of different species of arbuscular mycorrhizal fungi (HMA) (Latef and Chaoxing, 2011).

For their part, Gavito and Azcón-Aguilar (2012) found that organisms from cold zones tolerate low temperatures better than those from temperate zones, since they present genetic variations and plasticity, which allows them to adapt to these extreme environmental conditions. In broad beans grown in alkaline soils, inoculation of nitrogen-fixing bacteria and HMA increases plant growth measured as total dry biomass (Abd-Alla *et al*., 2014). It is extremely important to consider that, unlike agrochemicals, microbiological formulation products for their proper functioning depend on the ecological interactions between the strains of the formulation, the microbial communities present in the soil and the plant, in addition to the abiotic and climatic factors of the agroecosystem (Sruthilaxmi and Babu, 2017).

Most of the success in the operation of a microbiological product depends on the degree of ecological knowledge of the agroecosystem where the product will be applied and the characteristics of the strains to be used (Compant *et al*., 2019). It is a fact that not all microorganisms contained in these products work in the same way for all crops, this is because microorganisms have coevolved with plants in particular habitats, establishing specific interactions regulated by the agroclimatic factors of each region over time (Pérez-Jaramillo *et al*., 2018).

These soil properties and functions are the result of a complex network of microbial interactions, which are modulated by specific factors such as: 1) the microbiota present in each region; 2) the specific agroclimatic conditions of the site where the agroecosystem is established; 3) the genotype of the crop or crops established in the agroecosystem; and finally, 4) anthropocentric management and influence on the agroecosystem (Compant *et al*., 2019; Saad *et al*., 2020).

Until now, the formulators of biological products available in the Mexican market have focused on some specific qualities of certain microorganisms (Table 1), which has made genera such as *Bacillus*, *Trichoderma*, *Rhizophagus* or *Bauberia* attractive to the producer. However, the microorganisms with which the biological products are formulated are obtained from diverse environments and have not coevolved with the environment in which they are released, so they must adapt to the conditions of the environment and to the autochthonous populations of the agroecosystem (Basu *et al*., 2021).

Table 1. Biological products available in the Mexican market.

Type	Developer/manufacturer	Product	Microorganism
Soil conditioner	zare agrhos	Bioactive az	*Bacillus subtilis*, *B. amyloliquefaciens*, *B. liqueniformis*, *B. megaterium* y *B. micoides*
Bioestimulant	Indebio	Pseudofos	*Pseudomona fluorescens*
Biofertilizante	Agribest	Nitrobac plus	*Azospirillum brasiliensis*, *Azotobacter* spp., *Bacillus* spp.
	Agrokemyca	Proceveg plus	*Bacillus subtilis*, *Pseudomonas fluorescens*
	Activa	Hiper-gram	*Gluconacetobacter diazotrophicus*, *Azospirillum brasilense*, *Azotobacter* sp.
	Biofábrica	Hiper-glom	
	Siglo xxi	Ctospor	*Glomus intraradices*, *Pisolithus tinctorius*, *Rhizopogon*, *amylopogon*, *R. bilosuli*, *R. fulvigleba*, *R. luteolus*, *Lacaria bicolor*, *L. laccata*, *Scleroderma citrini*, *S. cepa*, *Trichoderma harzianum*, *T. reesei*, *Azospirillum brasiliense*, *Azobacter chroococcum*, *Bacillus megaterium*, *Pseudomonas flourescens*
	Biosustenta	Endospor	
	Bioqualitum	Fosfonat	
	INIFAP	Biocomposta Azofer plus Maxifer Rhizofer Micorrizafer Plus Ferbiliq, Ectomic Biosustenta Azospirillum Endomaz Rhizbio Rhizbio m+ Micofert Micbal	Rizobacterias fijadoras de nitrógeno, solubilizadoras de fósforo y promotoras del crecimiento, *Glomus intraradices*, *G. mosseae*, *G. brasilianum*, *G. clarum*, *G. deserticola*, *G. etunicatum*, *Gigaspora margarita*, *Trichoderma harzianum*, *T. reesei*, *T. viride*, *Gliocladium virens* *Glomus intraradices*, *G. mosseae*, *G. brasilianum*, *G. clarum*, *G. deserticola*, *G. etunicatum*, *Gigaspora margarita*

Type	Developer/manufacturer	Product	Microorganism
Biofortifier	INIFAP	Biosustenta Micorrizas Bactocrop	*Azospirillum brasiliense*, *Azotobacter chroococcum*, *Bacillus megaterium*, *Pseudomonas fluorescens* *Azospirillum brasilense*, hongos micorrízicos arbusculares *Azospirillum brasilense* *Azospirillum brasilense* *Rhizobium etli*, *Glomus Intraradices*, *Azospirillum brasilense*, *Glomus intraradices*, Ecto micorrizas *Azospirillum brasilense* *Azospirillum brasilense* *Rhizhobium etli* *Bacillus subtilis*, *B. megaterium*
Biofortifier	Biokrone Grupefagro	Glumix Irrigation Glumix Granulado Raizorg	Hongos micorrízicos vesículo arbusculares, *Glomus geosporum*, *G. fasciculatum*, *G. constrictum*, *G. tortuosum*, *G. intraradices*, *Azospirillum brasilense*, *Azotobacter* sp., *Rhizobium* spp., *Bacillus* spp. *Bacillus* spp., *Paenibacillus* spp.
Biofungicide	Agrokemyca altus biopharm agro&biotecnia/ibt-unam bactiva biocampo biosustenta biokrone	Hiper lisis Tricho hiper Castell Blitefree Fungifree-ab Bactiva, Biosan Multi-bac Folisan Tricsoil	*Bacillus subtilis*, *Pseudomonas fluorescens*, *B. cereus*, *B. megaterium*, *Lactobacillus* sp., *Trichoderma harzianum* *Streptomyces* spp., *Streptomyces jofer* *Trichoderma harzianum*, *T. reesei*, *T. viride*, *Gliocladium virens*, *Bacillus subtilis*, *B. polymyxa*, *B. megaterium*, *Pseudomonas*

Type	Developer/manufacturer	Product	Microorganism
		Natucontrol	*flourescens*, *Trichoderma*
		Baktillis	*harzianum*
		Biocontrol	
		fol	*Bacillus subtilis*, *B. pumilus*
			Bacillus subtilis
			Trichoderma harzianum
			Trichoderma harzianum
			Bacillus subtilis
Bioinsecticide	agrokemyca	Phyto	*Metarhizium anisopliae*, *Beauveria*
		control	*bassiana*
	Bactiva biosustenta	Lekany duo	*Isaria fumosorosea*, *Lecanicillium*
		Micotiva	*lecanii*, *Beauveria bassania*
	Biokrone BT	Probiol	
	agroindustrial		*Beauveria bassiana*, *Paecilomyces*
		BT krone	*fumosoroseus*, *Metarhizium*
	Ciasa agro	Turinsil	*anisopliae*, *Bacillus thuringiensis*
		BT+BMP	subsp. *Aizawai*, *Bacilus*
	Certis agro México	BTI	*thuringensis*
		Biopest max	*Bacillus thuringiensis*, *Beuveria*
	Grupe fagro		*bassiana*, *Metarhizium anisopliaea*,
	indebio	Double	*Paecilomyces* sp., *Bacilus*
		nickel 55	*thuringensis* var. israelensis,
	TNI	WG	*Beauveria bassiana*, *Nomurea*
		Crymax gda	*rileyi*, *Metarhizium anisopliae*,
	Zare agrhos	Javelin wg	*Verticillium lecanii*, *Paecilomyces*
		Biotech bmi	*fumosoroseus*
		Beapest	*Bacillus amyloliquefaciens*
		Fumpest	*Bacillus thuringiensis* var. kurstaki
		Lecapest	*Bacillus thuringiensis* var. kurstaki
		Metapest	*Beauveria bassania*, *Metarhizium*
		Thurinpest	*anisopilae*, *Isaria fumorosea*
		Micotiva	*Beauveria bassiana*, *Paecilomyces*
		plus	*fumosoroseus*, *Lecanicillium*
		Beazar	*lecanii*, *Metarhizium anisopliae*
		Controlkar	*Bacillus thuringiensis* var. kurstaki
		Fungimix az	*Beauveria bassiana*, *Metarhizium*
			anisopliae
			Beauveria bassiana, *Paecilomyces*
			fumosoroseus, *Paecilomyces*
			lilacinus, *Nomuraea rileyi*
			Beauveria bassiana, *Paecilomyces*
			fumosoroseus, *Metarhizium*
			anisopliae, *Verticilium lecanni*,
			Beauveria bassiana, *Nomuraea*

Type	Developer/manufacturer	Product	Microorganism
			rileyi, *Metarhizium anisopliae, Paecilomyces lilacinus, Paecilomyces fumosoroseus*
			Bacillus thuringiensis var. Kurstaki, *Metarhizium anisopliae*
			Heterorhabditis bacteriophora, *Paecilomyces fumoroseus*
Bioinsecticide-Bioacaricide	Aare agrhos	Thompzar	*Hirsutella thompsonii*
Bionematicide	Agrokemyca Biosustenta Grupofagro Indebio	Hiper nema Plus Plcinum® Nemabiol Plus Paepest Pochpest	*Paecilomyces lilacinus* *Purpureocillium lilacinum* *Bacillus subtilis*, *Trichoderma harzianum* *Paecilomyces lilacinus* *Pochonia clamydospora*
Physiological stimulant	Zare agrhos	Biozar	*Ascophyllum nodossum*
Inoculant for seed	Zare agrhos	Nitrozar	*Rhizobium* spp.
Soil improver	Zare agrhos	Biofrex Fijabiol k	*Bacillus* spp. *Frateuria* spp.

Considering that the use of microorganisms in agriculture follows ecological principles in which the proper functioning and balance of the agroecosystem is sought, it is necessary to correctly choose an input formulated with microorganisms for the field. However, it is still largely unknown what happens when microorganisms are released into agroecosystems, as well as the ecological implications that could arise with the applications of these repeatedly and constantly over time (Hart *et al*., 2017).

Therefore, when using a product of microbiological formulation, it must be taken into account: 1) the strains used do not represent a risk to human, animal or plant health, so it is recommended that they have a high expression of virulence factors; 2) the strains are native to the agroecosystem in which they are intended to be applied, in such a way that their activity is easily associated with the environment in which they will be released; and 3) have microbiological studies that allow adequate decision-making regarding the use and management of strains (Basu *et al*., 2021).

Advances in government policy regarding the use of microbial inoculants in Mexico

There are specific issues that would allow generating important advances in the use of these microorganisms in the development of a sustainable agriculture in Mexico, the topics are concentrated in four general aspects: i) update in the technological development of microbial products by specialists in the field; ii) promotion of the link between science and private industry; iii) implementation of programs to promote and support research into microbial developments; and iv) establishment of national legislation on the proper use of these products (Salgado-Sánchez, 2015).

Mexico has a wide network of institutions committed to the development of microbial products and highly trained human resources in the area, so various research programs on microorganisms have been consolidated in many academic entities throughout the country and today there is a growing supply of specialists in this area, many of these institutions already provide services to the industry and it is increasingly common to develop joint research and technology transfer (Chávez-Díaz *et al*., 2020).

In addition, some scientists have begun to generate interest in the spin-offs, companies that derive from technological developments carried out in universities or research centers, with a license to use this technology, since they offer the industry very specialized products and services that could be of great help to the sustainable development of our country (Hernández *et al*., 2017). The still limited number of laws, rules and regulations regulating the development of technologies based on microorganisms and their use in sustainable agriculture implies a lag in the growth of the country's agriculture (Sabourin *et al*., 2017).

In Mexico, there are efforts in regulatory matter such as the Official Mexican Standard NOM-077-FITO-2000. Studies of biological effectiveness in plant nutrition inputs for agricultural use and their 'technical opinion', official standard in which the requirements and specifications for the realization of studies of biological effectiveness of plant nutrition inputs are established; however, the generation or updating of standards for those technologies based on microorganisms is decisive, since it focuses mainly on chemical nutrition rather than biological and copyright protection has not yet been addressed in a diligent manner.

Therefore, continuing to develop strategies to solve the challenges and considerations to promote sustainable development using microorganisms will strengthen both the primary sector and various existing productive sectors, generating a supply of greater added value to agricultural products. As well, it can contribute to solving many social needs that are identified in Mexico and worldwide, such as: food supply, care of natural resources, care of the environment and improve the quality of life, to name a few.

Perspectives for the dissemination of the use of microbial inoculants in Mexico

In Mexico, the use of microorganisms in agriculture has advanced through the last decades; ensuring that these advances permeate producers through dissemination is the best way for science to be increasingly seen as a necessary tool in the sustainable development of our country.

In this sense, in the National Institute of Forestry, Agriculture and Livestock Research (INIFAP), various efforts have been developed and consolidated in terms of dissemination of the use of microorganisms in agriculture in Mexico, such as the AgroEvento 2020 'biological products, a tool to potentiate the Mexican countryside' (AgroEvento, 2020), organized by the National Center for Genetic Resources (CNGR) of INIFAP and the Technological Institute of Sonora, this event aimed to bring together academics, scientists, students, technicians, advisors, trainers, marketers, producers of agricultural inputs and farmers to share their experiences, knowledge and perspectives regarding the use of biological products, or other agrobiotechnologies for sustainable innovation as an alternative to conventional agricultural production in Mexico.

This type of events allows Mexican researchers involved in the development and implementation of technologies based on microorganisms that favor the conservation and use of national biodiversity, with this type of actions, producers and people in the agricultural sector are informed about the advances in isolation, identification, and characterization of beneficial microorganisms for crops, design, application, management and formulation of biological formulation products for the countryside. Efforts such as this should be promoted to ensure that producers have access to information and can decide how to take advantage of advances in the use of microorganisms in agriculture with the support of scientific research.

Conclusions

To ensure the correct use of microorganisms in sustainable agriculture, the profitability of these for the farmer must be ensured, but that at the same time it is friendly to the environment. This is achieved by carrying out agronomic practices where there is the use of microbial inoculants, of proven activity and purity, which assure the farmer an adequate specific number per species, which give him guarantee of quality and therefore confidence.

In the country there are problems such as the recovery of soils and the improvement in the productivity of crops where the use of microorganisms is a promising alternative. This solution is possible if it is planned with sustainability criteria, involving microbiological solutions, with new products with little or no impact on the environment.

Mexico has the responsibility to make progress in obtaining microbial inoculants that are safe for the farmer, capable of achieving increases in crop yields and that are also safe for the agroecosystem. The proper use of microorganisms in sustainable agriculture in Mexico has been unattended due to the lack of regulation and the indiscriminate use of them, so it is necessary to link the use of these microbial inoculants with the improvement in food production, by taking actions to use, restore and preserve microorganisms as a genetic resource.

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Cited literature

Abd-Alla, M. H.; El-Enany, A. W. E.; Nafady, N. A.; Khalaf, D. M. and Morsy, F. M. 2014. Synergistic interaction of rhizobium leguminosarum BV. Viciae and arbuscular mycorrhizal fungi as a plant growth promoting biofertilizers for faba bean (*Vicia faba* L.) in alkaline soil. Microbiol. Res. 169(1):49-58. https://doi.org/10.1016/j.micres.2013.07.007.

Agroevento. 2020. http://cmcnrg.inifap.gob.mx.

Bajsa, N.; Morel, M. A.; Braña, V. and Castro-Sowinski, S. 2013. The effect of agricultural practices on resident soil microbial communities: focus on biocontrol and biofertilization. Mol. Microbial Ecol. Rhizosphere. 2:687-700.

Basu, A.; Prasad, P.; Das, S. N; Kalam, S.; Sayyed, R. Z; Reddy, M. S. and Enshasy, H. E. 2021. Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: recent developments, constraints, and prospects. Sustainabiliy. 13(3):1140. https://doi.org/10.3390/ su13031140.

Basu, S. and Kumar, G. 2020. Stress signalling in the phytomicrobiome: breadth and potential. *In*: kumar, M.; Kumar, V. and Prasad, R. (Ed.). Phyto-microbiome in stress regulation. Springer, Singapore. 245-268 pp. https://doi.org/10.1007/978-981-15-2576-6_12.

Bergel, S. D. 2020. Desarrollo sustentable y medio ambiente: la perspectiva latinoamericana. Alegatos. 1(24):196-221.

Chávez-Díaz, I. F.; Zelaya-Molina, L. X.; Cruz-Cárdenas, C. I.; Rojas-Anaya, E.; Ruíz-Ramírez, S. y Santos-Villalobos, S. 2020. Consideraciones sobre el uso de biofertilizantes como alternativa agro-biotecnológica sostenible para la seguridad alimentaria en México. Rev. Mex. Cienc. Agríc. 11(6):1423-1436.

Compant, S.; Samad, A; Faist, H. and Sessitsch, A. 2019. A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. J. Adv. Res. 19:29-37. https://doi.org/10.1016/j.jare.2019.03.004.

Córdova, A.; Liliana, C.; Zelaya, M.; Lily, X.; Ávila, A.; Norma, V. R.; Valeria, C. M.; Nelly, E.; Parra, C.; Fannie, I.; Burgos, C.; Yamily, Y.; Chávez, D.; Ismael, F.; Fajardo, F.; Marja, L.; Santos, V. and Sergio, D. 2021. Omics sciences potential on bioprospecting of biological control microbial agents: the case of the Mexican agro-biotechnology. Rev. Mex. Fitopatol. 39(1):147-184.

De los Santos, V. S.; Parra-Cota, F. I.; Herrera-Sepúlveda, A.; Valenzuela-Aragón, B. y Estrada-Mora, J. C. 2018. Colmena: colección de microorganismos edáficos y endófitos nativos, para contribuir a la seguridad alimentaria nacional. Rev. Mex. Cienc. Agríc. 9(1):191-202.

Delgado-Baquerizo, M.; Maestre, F. T.; Reich, P. B.; Jeffries, T. C.; Gaitan, J. J.; Encinar, D.; Berdugo, M.; Campbell, C. D. and Singh, B. K. 2016. Microbial diversity drives multifunctionality in terrestrial ecosystems. Nat. Comm. 7(1):1-8.

Díaz-Rodríguez, A. M.; Salcedo, L. A.; Felix, C. M.; Parra-Cota, F. I.; Santoyo, G.; Puente, M. L.; Bhattacharya, D.; Mukherjee, J. and De los Santos, V. S. 2021. The current and future role of microbial culture collections in food security worldwide. Front. Sustain. Food Syst. 4:614739.

Dohrmann, A. B.; Küting, M.; Jünemann, S.; Jaenicke, S.; Schlüter, A. and Tebbe, C. C. 2013. Importance of rare taxa for bacterial diversity in the rhizosphere of Bt-and conventional maize varieties. The ISME journal. 7(1):37-49.

Fielding, K. S.; Terry, D. J.; Masser, B. and Hogg, M. A. 2008. Integrating social identity theory and the theory of plannedbehaviour to explain decisions to engage in sustainable agricultural practices. Br. J. Soc. Psychol. 47(1):23-48.

FAO. 2017. Food and Agriculture Organization of the United Nations. Towards zero hunger and sustainability. The FAO multipartner programme support mechanism. http://www.fao.org/documents/card/es/c/fa6a801c-5bd4-4522-a2ff-bfbef1e56529.

Gavito, M. E. and Azcón-Aguilar, C. 2012. Temperature stress in arbuscular mycorrhizal fungi: a test for adaptation to soil temperature in three isolates of *Funneliformis mosseae* from different climates. Agr. Food Sci. 21(1):2-11. https://doi.org/10.23986/afsci.4994.

Hernández, R. V. R.; Escandón, J. M. S.; Mendoza, A. L. and Izaguirre, J. A. H. 2017. La tecnología: una herramienta de apoyo para pymes y emprendedores desde el entorno universitario. Ciencia ergo-sum, Rev. Cient. Multidisciplinaria de Prospectiva. 24(1):75-82.

Ibarra-Villarreal, A.; Gándara-Ledezma, A.; Godoy-Flores, A.; Díaz-Rodríguez, A. M.; Parra-Cota, F. I. and De los Santos, V. S. 2021. Salt-tolerant bacillus species as a promising strategy to mitigate the salinity stress in wheat (Triticum turgidum subsp. durum). J. Arid Environ. 186:104399.

Joshi, H.; Somduttand, C. P. and Mundra, S. L. 2019. Role of effective microorganisms (EM) in sustainable agriculture. Inter. J. Curr. Microbiol. Appl. Sci. 8(3):172-181.

Khalid, A.; Arshad, M.; Shaharoona, B. and Mahmood, T. 2009. Plant growth promoting rhizobacteria and sustainable agriculture. *In*: Khan, M. S.; Zaidi, A. and Musarrat, J. (Ed.). Microbial strategies for crop improvement. Springer, Berlin, Heidelberg. 133-160 p. https://doi.org/10.1007/978-3-642-01979-1_7.

Latef, A. A. H. A. and Chaoxing, H. 2011. Arbuscular mycorrhizal influence on growth, photosynthetic pigments, osmotic adjustment and oxidative stress in tomato plants subjected to low temperature stress. Acta Physiologiae Plantarum. 33:1217-1225. https://doi.org/10.1007/s11738-010-0650-3.

López, J. y Rodríguez, R. 2014. Agricultura biointensiva: método de agricultura sostenible para los microagricultores de México. *In*: XVIII Congreso Internacional de Investigación en Ciencias Administrativas. 2434-2455 p.

Orozco-Mosqueda, M. y Santoyo, G. 2020. Bacterias promotoras del crecimiento vegetal: aspectos básicos y aplicaciones para una agricultura sostenible. Primera (Ed.). Fontamara. Ciudad de México, México. 240 p.

Pastor-Pérez, M. D. P.; Ramos-Ávila, A. E. y Santa María-Torres, A. 2016. Evaluación de la sustentabilidad: una reflexión a partir del caso de la red nacional de desarrollo rural sostenible (México). Entreciencias: diálogos en la sociedad del conocimiento. 4(9):61-72.

Pérez-Jaramillo, J. E.; Carrión, V. J.; Hollander, M. and Raaijmakers, J. M. 2018. The wild side of plant microbiomes. Microbiome. 6:143. https://doi.org/10.1186/s40168-018-0519-z.

Reganold, P. J. and Wachter, J. M. 2016. Organic agriculture in the twenty-first century. Nature Plants. 2:1-8.

Richardson, A. E. and Simpson, R. J. 2011. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. Plant Physiol. 156(3):989-996. https://doi.org/10.1104/pp.111.175448.

Rojas-Padilla, J.; Chaparro-Encinas, L. A.; Robles-Montoya, R. I. y De los Santos, V. S. 2020. Promoción de crecimiento en trigo (*Triticum turgidum* L. subsp. Durum) por la co-inoculación de cepas nativas de Bacillus aisladas del valle del Yaqui, México. Nova Scientia. 12(24):1-27.

Saad, M. M.; Eida, A. A. and Hirt, H. 2020. Tailoring plant-associated microbial inoculants in agriculture: a roadmap for successful application. J. Exp. Bot. 71(13):3878-3901. doi:10.1093/jxb/eraa111.

Sabourin, E. P.; Patrouilleau, M. M.; Le-Coq, J. F.; Vásquez, L. y Niederle, P. A. 2017. Políticas públicas a favor de la agroecología en América Latina y el Caribe. Red políticas públicas en América Latina y el Caribe (Red PP-LA). 213 p.

SAGARPA. 2014. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA). México: el sector agropecuario ante el desafío del cambio climático. Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO).

Salgado-Sánchez, R. 2015. Agricultura sostenible y sus posibilidades en relación con consumidores urbanos. Estudios Sociales. 23(45):113-140.

Sosa, B. A. 2017. La disponibilidad de alimentos en México: un análisis de la producción agrícola de 35 años y su proyección para 2050. Papeles de Población. 23(93):207-230.

Sruthilaxmi, C. B. and Babu, S. 2017. Microbial bio-inoculants in Indian agriculture: ecological perspectives for a more optimized use. Agri. Ecosyst. Agroecosyst. Environ. 242(1):23-25. http://dx.doi.org/10.1016/j.agee.2017.03.019.

Urquía-Fernández, N. 2014. La seguridad alimentaria en México. Salud Pública de México. 56(1):92-98.

Valenzuela-Aragón, B.; Parra-Cota, F. I.; Santoyo, G.; Arellano-Wattenbarger, G. L. and De los Santos, V. S. 2019. Plant-assisted selection: a promising alternative for in vivo identification of wheat (*Triticum turgidum* L. subsp. Durum) growth promoting bacteria. Plant and Soil. 435(1-2):367-384.

Valenzuela-Ruiz, V.; Gálvez-Gamboa, G. T.; Villa-Rodríguez, E.; Parra-Cota F. I.; Gustavo, S. y De los Santos, V. S. 2020. Lipopéptidos producidos por agentes de control biológico del género Bacillus: revisión de herramientas analíticas utilizadas para su estudio. Rev. Mex. Cienc. Agríc. 11(2):419-432.

Villegas-Olivera, J. A.; J. Pérez-Moreno, G.; Mata, J. J.; Almaraz-Suárez, D.; Ojeda, T. and. Espinosa-Hernández, V. 2017. Type of light and formation of basidiomata of two species of edible ectomycorrhizal mushrooms associated with neo-tropical pines and the description of basidiomata development. Rev. Fitotec. Mex. 40(4):405-413.

Waseem, R.; Gershom, E. M. G. E.; Waseem, F.; Khan, H.; Ghulam, M.; Panhwar, M. G. and Shi, Y. 2020. Adoption of sustainable agriculture practices in banana farm production: a study from the sindh region of pakistan. Intr. J. Env. Res. Publ. Health. 17:3714-3728.